Drying of Corn Kernels: From Experimental Images to Multiscale Multiphysics Modeling

Pawan S. Takhar[1*], and Shuang Zhang[2]
[1]Texas Tech University, [2]Visualization Sciences Group Inc.
* Author has previously published as Pawan P. Singh
* Corresponding author: Address – Box 42141, Animal and Food Sciences, Texas Tech University, Lubbock, TX, 79409-2141, Email - pawan.takhar@ttu.edu

Introduction *(Mandatory)*

Corn kernels have a complex structure as they are composed of a pericarp layer outside and contain hard and soft endosperm and germ components. Corn kernels are harvested around 30% moisture content on dry basis and dried to about 12% moisture content using heated air. Drying helps to lower the water activity to increase their shelf life. If the drying is not controlled properly, the kernels develop stress cracks, which makes them prone to insect and microbial damage.

To study and control the drying process, multiscale and multiphysics simulation conducted on the real corn kernel geometry is necessary. While the complex corn kernel structure make it extremely challenging to model accurately, this paper adapted an experimental image to simulation workflow, where the geometry are reconstructed from 3D imaging experiments. The resulting geometry, containing all the fidelity of the real-world, is then meshed and simulated with multiphysics, multiscale numerical model.

Geometry reconstruction

To create the corn's 3D geometry, a micro-CT (computed tomography[5]) scan was performed at a resolution of 2.7392 micro meter in x, y and z directions. The 2D slices obtained using micro CT were reconstructed into a 3D object using Avizo [1]. Automatic and interaction segmentation algorithms were adopted to segment the corn kernel into various components such as hard endosperm, soft endosperm and germ. The kernel was dissected into half to save computational time, before STL surfaces are then reconstructed.

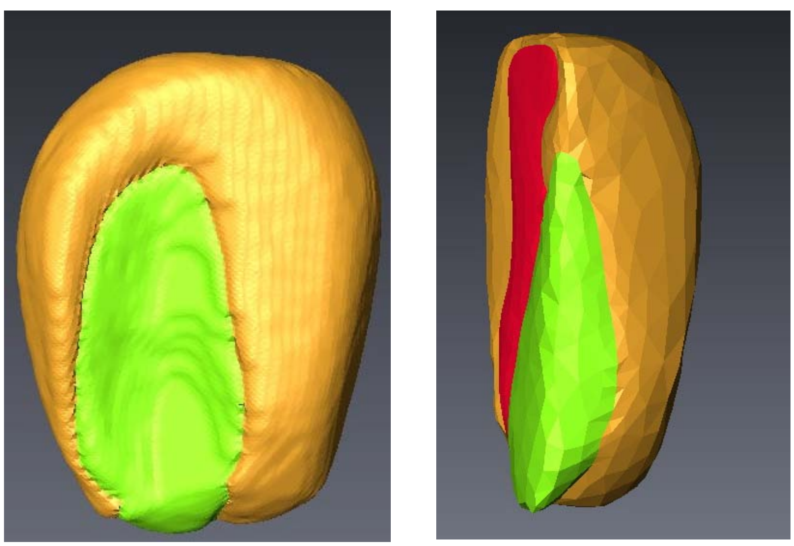

Figure 1 Geometry reconstruction with Avizo. Left: full geometry. Right: half of the geometry.

The 3D surface is then meshed with tetrahedron element and exported to Comsol.

COMSOL Multiphysics Simulation

Multiscale fluid transport model of Singh, Maier et al [3] was used to model moisture diffusion in corn kernels.

$$\dot{\varepsilon}^f + \left(\varepsilon^f - 1\right)\nabla_{\mathbf{E}} \cdot \left(D\nabla_{\mathbf{E}}\varepsilon^f\right) - \left(\varepsilon^f - 1\right)\nabla_{\mathbf{E}} \cdot \left[\int_0^t B_v(t-\tau)\nabla_{\mathbf{E}}\dot{\varepsilon}^f(\tau)d\tau\right] = 0,$$

$$B_v(t) = B_c G(T, \varepsilon^f; t).$$

where, various symbols are given as

$B_v(t)$	Memory function
B_c	Coefficient multiplying G(t) to convert it into force term.
D	Darcian (Fickian) diffusion coefficient
$G(t)$	Stress relaxation function
t	Time
T	Temperature
ε^f	Total volume fraction of interacting fluid (water) in the macroscale REV (= sum of volume fractions of adsorbed fluid and bulk fluid)
$\nabla_{\mathbf{E}}$	Del operator in Eulerian coordinates

The equation couples the effect of viscoelastic relaxation given by the time integral to moisture diffusion. This makes the equation predict non-Fickian transport in the vicinity of glass transition. Corn kernels exhibit glass transition in drying temperature and moisture content range used in the industry [2]. The boundary condition used for the solution of above equation was of Dirchlet type for the germ part and of Neumann type for the endosperm part.

Preliminary Results

The following two figures show the distribution of moisture content at two drying conditions (figure 2 at 29 C temperature and 48% relative humidity and figure 3 at 87C temperature and 14% relative humidity). The figures show that greater moisture gradient is observed between germ and endosperm. This makes corn prone to formation of cracks near the germ. At higher temperature higher gradient is observed. These results agree with that of Song and Litchfield [4] who made similar observation using magnetic resonance imaging.

Figure 4 and 5 shows moisture distribution across cross-section. In both figures, the profiles from top toward bottom are at intervals of 0min, 15min, 30min, 60min, 120min, 180min, 240min. Left of the figure is center of kernel, right is the external surface.

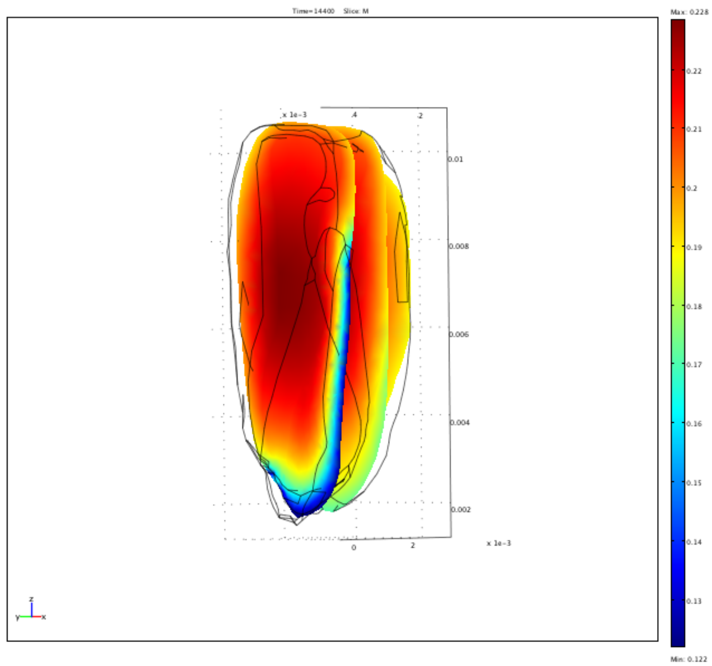

Figure 2. Low temperature moisture content distribution after 4 hrs of drying.

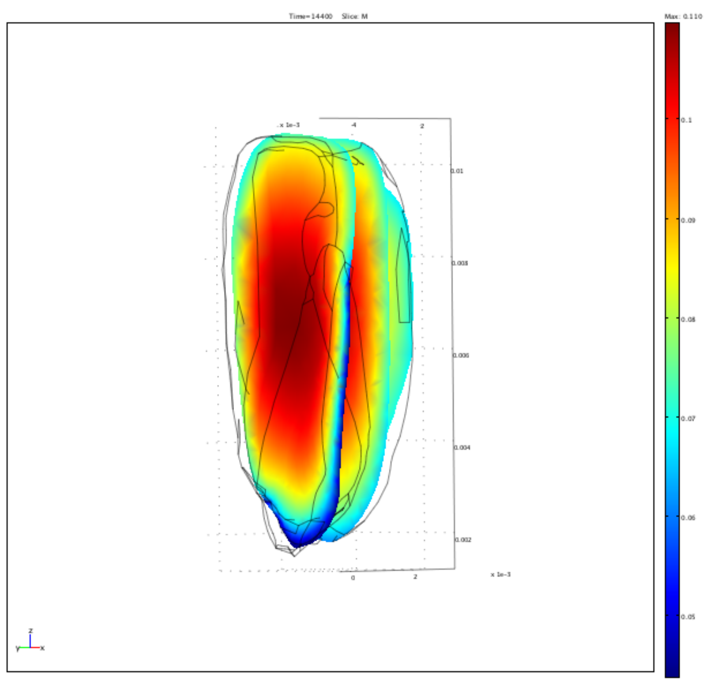

Figure 3. High temperature moisture content distribution after 4 hrs of drying.

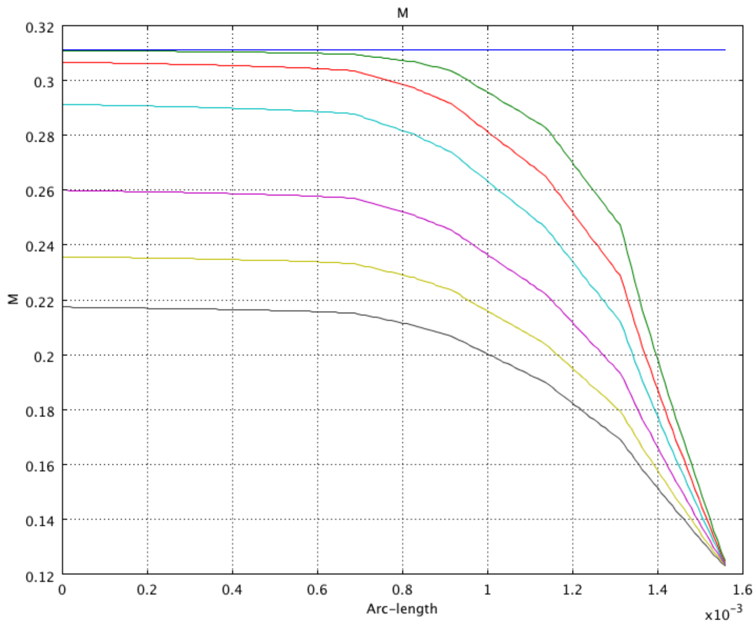

Figure 4. Moisture distribution at 29C temp and 48% RH.

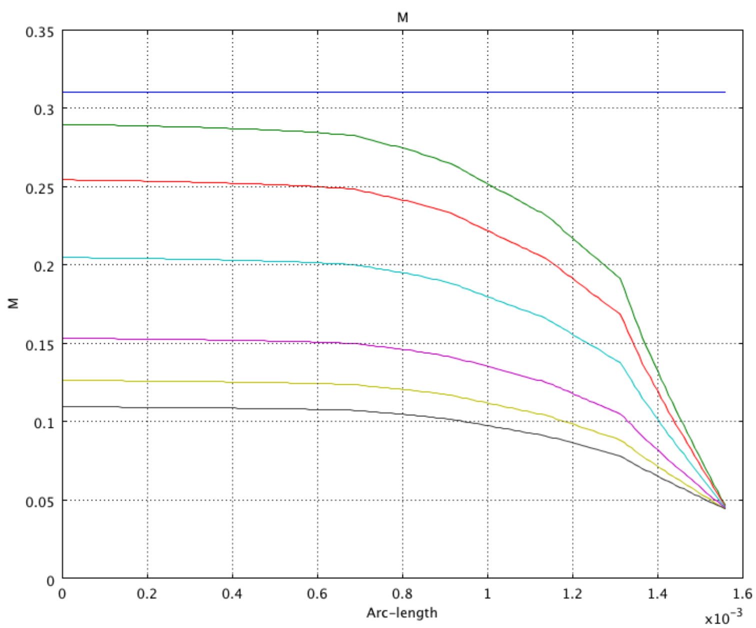

Figure 5. Moisture distribution at 87C temp and 14% RH.

At high temperature greater reduction in moisture is caused in the same time, which causes faster drying. However, greater moisture gradients are developed which may make corn prone to cracking. By performing simulations with various combinations of drying air and temperature, optimum drying conditions causing sufficient moisture loss and minimal crack formation can be obtained.

Conclusion

This work demonstrated the importance and feasibility of experimental image to simulation workflow, which opens the door to vast number of applications requiring the real world geometry. Moreover, the workflow is successfully applied to a food processing study, where multiphysics and multiscale modeling based on 3D experimental image reconstruction contributes to the preservation of corn, one of the major food sources for the world population.

Acknowledgements

PST thanks to USDA-CSREES for providing the financial support under the award number 2003-35503-13963.

References

1. Avizo software website, http://www.vsg3d.com, 2009.
2. J. Hundal and P. S. Takhar. "Dynamic viscoelastic properties and glass transition behavior of corn kernels." *International Journal of Food Properties* **12**(2): 295 - 307 (2009).
3. P. P. Singh, D. E. Maier, et al. "Effect of viscoelastic relaxation on moisture transport in foods. Part I: Solution of general transport equation." *Journal of Mathematical Biology* **49**(1): 1-19 (2004).
4. H. P. Song and J. B. Litchfield. "Measurement of stress cracking in maize kernels by magnetic-resonance-imaging." *Journal of Agricultural Engineering Research* **57**(2): 109-118 (1994).
5. S. Zhang, P. Barthelemy, et al. “Advanced 3D Data Analysis and Visualization in Aluminum Die Casting using Computed Tompgraphy”. *Proceedings of Materials Science & Technology 2009*, Pittsburg, PA, October 2009.